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Mass Accretion Processes in Young Stellar Objects: Role of Intense Flaring Activity

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Abstract

According to the magnetospheric accretion scenario, young low-mass stars are surrounded by circumstellar disks which they interact with through accretion of mass. The accretion builds up the star to its final mass and is also believed to power the mass outflows, which may in turn have a significant role in removing the excess angular momentum from the star-disk system. Although the process of mass accretion is a critical aspect of star formation, some of its mechanisms are still to be fully understood. On the other hand, strong flaring activity is a common feature of young stellar objects (YSOs). In the Sun, such events give rise to perturbations of the interplanetary medium. Similar but more energetic phenomena occur in YSOs and may influence the circumstellar environment. In fact, a recent study has shown that an intense flaring activity close to the disk may strongly perturb the stability of circumstellar disks, thus inducing mass accretion episodes (Orlando et al. 2011). Here we review the main results obtained in the field and the future perspectives.

Keywords: accretion, accretion disks - MHD - stars: circumstellar matter - stars: flare - stars: pre-main-sequence - X-rays: stars.

1 Introduction

Observations in the X-ray band reveal that low-mass pre-main-sequence stars are strong sources with X-ray luminosities $3-4$ orders of magnitude greater than that of the present-day Sun. The source of this high-energy radiation is plasma with temperatures of $1-100$ MK in the stellar outer atmospheres (coronae), heated by magnetic activity analogous to the solar one but higher by factors up to 10^6. Such a magnetic activity manifests through very different phenomena that may occur in several places of the stellar atmosphere and circumstellar environment. The young star interacts with its disk in a complex fashion, with accretion and ejection of collimated outflows. Strong magnetic fields are believed to connect the star with a Keplerian circumstellar disk, funneling accretion onto limited portions of the stellar surface (e.g. Hartmann 1998) where shocks are produced by the impact of the accretion streams (e.g. Orlando et al. 2010).

X-ray flares are violent manifestations of the stellar magnetic activity and are triggered by an impulsive energy input from coronal magnetic fields. X-ray observations in the last decades have shown that flares in young stellar objects (YSOs) have amplitudes much larger than solar analogues and occur much more frequently. Examples of these flares are those collected by the Chandra satellite in the Orion star-formation region (COUP enterprise; Favata et al. 2005). In the Sun, such energetic events are often associated to coronal mass ejections and give rise to perturbation effects of the interplanetary medium, broadly known as space weather effects. Similar phenomena are expected to occur in young stars, and may affect the circumstellar environment. For instance, Favata et al. (2005) analyzed the most energetic flares observed by COUP and found that these flares might be hosted in magnetic loops extending several stellar radii, much larger than ever observed in older stars. Since the central star is surrounded by a circumstellar disk accreting material onto the star, it is natural to ask whether strong flaring activity involves the disk and even perturbs its stability, possibly affecting the mass accretion to the star.

At the present time, in fact, it is unclear where these flares occur. The differential rotation of the disk together with the interaction of the disk with the magnetosphere may cause magnetic reconnection close to the disk's surface, triggering large-scale flares there. In this case, the flares may perturb the stability of the circumstellar disk causing, in particular, a strong local overpressure. The pressure gradient force might be able to push disk's matter out of the equatorial plane into funnel streams, thus providing a mechanism to drive mass accretion that differs from that, commonly invoked in the literature, based on the disk viscosity (Romanova et al. 2002). Bright flares close to circumstellar disks may therefore have important implications for a number of issues such as the transfer of angular momentum and mass between the star and the disk, the powering of outflows, and the ionization of circumstellar disks.

Recently, we have investigated the idea that an intense flare close to an accretion disk may perturb the stability of the disk and trigger mass accretion onto the star (Orlando et al. 2011). In this paper we review our findings and present preliminary results of a study investigating the effects of a storm of small-to-medium flares on the stability of accretion disks (Orlando et al. 2014). In Sect. 2 we describe the MHD model; in Sect. 3 we present the results; in Sect. 4 we draw our conclusions.

2 The MHD Model

The model describes a classical T Tauri star (CTTS) of mass $M_* = 0.8 M_\odot$ and radius $R_* = 2R_\odot$ located at the origin of a 3D spherical coordinate system (see Orlando et al. 2011 for a detailed description). We adopted the initial conditions introduced by Romanova et al. (2002). In particular, we assumed the rotation period of the star to be 9.2 days as representative of CTTSs. The initial unperturbed stellar atmosphere is approximately in equilibrium and consists of three components: the stellar magnetosphere, the extended stellar corona, and the Keplerian disk. Initially, the magnetosphere is assumed to be force-free, with dipole topology and magnetic moment aligned with the rotation axis of the star. The magnetic moment is chosen in order to have a magnetic field strength of the order of 1 kG at the stellar surface. The isothermal disk is cold, dense and rotates with angular velocity close to the Keplerian value; its rotation axis (coincident with the rotation axis of the star) is aligned with the magnetic moment. The disk is initially truncated by the stellar magnetosphere at the radius R_d where the ram pressure of the disk is equal to the magnetic pressure; for the adopted parameters, $R_d = 2.86 R_*$ and the co-rotation radius is located at $R_{co} = 9.2 R_*$. The corona is initially isothermal with temperature $T = 4$ MK and at low density.

The system is described by the time-dependent MHD equations of mass, momentum, and energy conservation in a 3D spherical coordinate system, extended with gravitational force, viscosity of the Keplerian disk, thermal conduction (including the effects of heat flux saturation), coronal heating (via a phenomenological term), and radiative losses from optically thin plasma (see Orlando et al. 2011 for more details). The phenomenological heating is prescribed as a component, describing the stationary coronal heating, plus a transient component, triggering the flares. The calculations were performed using PLUTO (Mignone et al. 2007), a modular, Godunov-type code for astrophysical plasmas.

3 Results

As a first application of the model, we have investigated the effects of a single bright flare on the stability of the disk (Orlando et al. 2011). The initial heat pulse triggering the flare is released at a distance of $5R_*$, namely in a region comprised between the truncation and corotation radii, and it is supposed to be indicative of a likely area of magnetic reconnection. Heat pulses occurring closer to the inner disk edge are expected to produce analogous perturbations on the disk dynamics. We followed the evolution of the star-disk system for ≈ 2 days. After the heat pulse has been released, an MHD shock wave develops above the disk and propagates away from the protostar. The heat deposition determines a local increase of temperature and pressure. Disk material is heated and expands with a strong evaporation front which is channeled along the magnetic field lines towards the central star. After ~ 1 hour a hot loop forms linking the disk with the star (see upper panel in Fig. 1). The loop has an effective maximum temperature of ≈ 100 MK (at the peak of emission measure) and a length of $\approx 10^{12}$ cm; these values are in good agreement with those inferred from the analysis of the brightest flares observed by COUP (Favata et al. 2005). The overheating of the disk surface makes a significant amount of material expand and be ejected in the magnetosphere. A small fraction of this material fills the loop whose density increases from 10^8 cm^{-3} to 10^{10} cm^{-3}. On the other hand, most of the expanding disk material is not confined by the magnetic field and is ejected away from the star, carrying away mass and angular momentum.

During the evolution of the hot loop, an overpressure wave develops where the heat pulse has been injected. This overpressure travels through the disk and reaches the opposite boundary after ≈ 5 hours. There the pressure gradient force drives the material out of the disk and channels it into a funnel flow. Then the gravitational force accelerates the escaped material toward the central star where the stream impacts ≈ 25 hours after the injection of the heat pulse. The accretion flow persists until the end of the simulation ($t = 48$ h). The lower panel in Fig. 1 shows a cutaway view of the star-disk system after the impact of the stream onto the stellar surface. We found that the dynamics and physical characteristics of the accretion stream triggered by the flare closely recall those of streams driven by the accumulation of mass at the disk truncation radius under the effect of the viscosity and pushed out of the equatorial plane because of the growing pressure gradient there (e.g. Romanova et al. 2002).

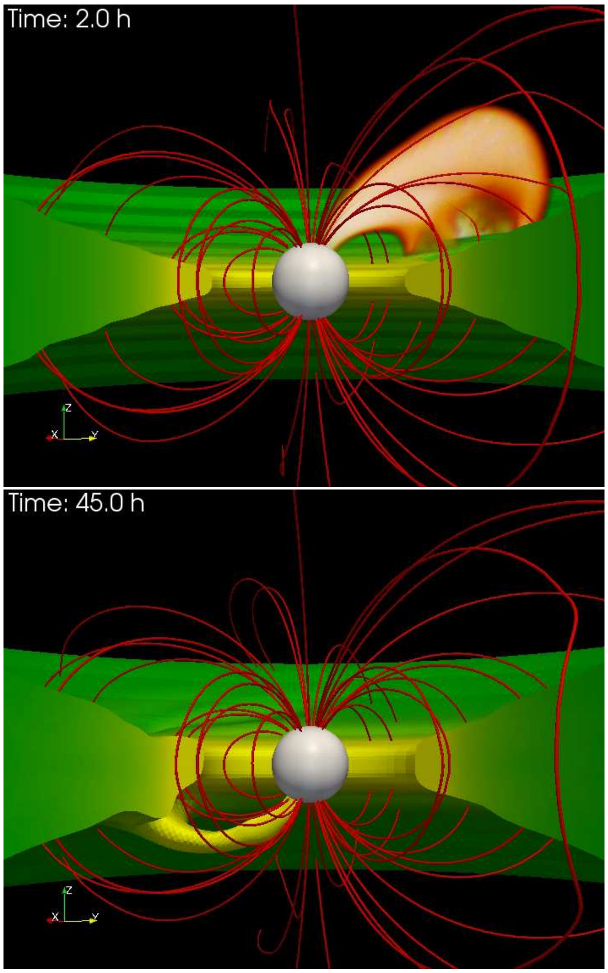

Figure 1: Effects of a single bright flare on the stability of the circumstellar disk. Cutaway views of the star-disk system showing the mass density of the disk (yellow-green) at $t = 2.0$ hours (upper panel) and at $t = 45$ hours (lower panel) since the injection of the heat pulse. The upper panel also over-plots the three-dimensional volume rendering of the plasma temperature (MK), showing the flaring loop (in red) linking the inner part of the disk with the star. The lower panel shows the accretion stream triggered by the flare in the side of the disk opposite to the flaring loop. Selected magnetic field lines are overplotted in red.

From the simulation, we derived also the mass accretion rate and found $\dot{M} > 2.5 \times 10^{-10}\, M_{\odot}$ yr^{-1}. We compared this rate with those inferred from optical observations of CTTSs (Herczeg & Hillenbrand 2008; Curran et al. 2011) and found a good agreement. We concluded that a bright flare as those frequently detected in YSOs (e.g. COUP observations) can be an efficient mechanism to trigger accretion onto the protostar itself with accretion rates on the same order of those commonly measured in CTTSs.

As a follow-up of the previous study, we explored in more details the possibility that significant mass accretion in young stars can be triggered by a storm of small-to-medium flares (as those frequently observed) occurring on the accretion disk (Orlando et al. 2014). To this end, we performed a 3D MHD simulation analogous to that described in Orlando et al. (2011) but considering a storm of flares distributed randomly in proximity of the disk surface instead of a single bright flare.

We found that each simulated flare follows an evolution similar to that of the single bright flare described in Orlando et al. (2011). The main difference is that, now, interactions between next flares may occur. Figure 2 shows cutaway views of the star-disk system after $\approx$ 26 hours. During the system evolution, the flares build up an extended corona linking the star with the disk. At the same time, the disk is strongly perturbed by the flares and, after $\approx$ 20 hours, several funnel streams develop, accreting substantial mass onto the star (see lower panel in Fig. 2). The streams persist until the end of the simulation and last for a time longer than the typical interval between flares. The simulated mass accretion rate is $10^{-10} < \dot{M} < 10^{-9}\, M_{\odot}\mathrm{yr}^{-1}$, again in good agreement with the values inferred from optical observations of CTTSs (Herczeg & Hillenbrand 2008; Curran et al. 2011).

4 Conclusions

We investigated the effects of an intense flaring activity on the stability of a circumstellar disk surrounding a magnetized CTTS. To this end, we developed a 3D MHD model including, for the first time, all key physical processes, most notably the thermal conduction and the radiative losses from optically thin plasma. As a first step, we analyzed the perturbation induced by a single bright flare occurring in proximity of the disk (Orlando et al. 2011). Then, we investigated the effects of a storm of small-to-medium flares distributed randomly close to the disk (Orlando et al. 2014). Our findings lead to the following conclusions: (a) flares occurring close to the circumstellar disk can trigger substantial and persistent accretion flows, similar to those caused by the disk viscosity; (b) an intense flaring activity close to the disk builds up an extended corona linking the star to the disk.

In the case of a single bright flare occurring close to the disk, the simulations suggest that mass accretion events associated with X-ray flares should be observed. However, correlation between UV/optical accretion tracers and X-ray flux is rarely seen (Stassun et al. 2006). On the other hand, such a correlation is not prediced by simulations describing a continuous flaring activity close to the disk (Orlando et al. 2014). In this case, the streams are triggered by the first flares at the beginning of the simulation and then are continuously powered by the following ones. At regime, therefore, no clear correlation between UV/optical accretion tracers and X-ray flux is foreseen. In the light of the above findings, we suggest that the flaring activity common to YSOs may turn out to be important in the exchange of angular momentum and mass between the circumstellar disk and the central protostar.

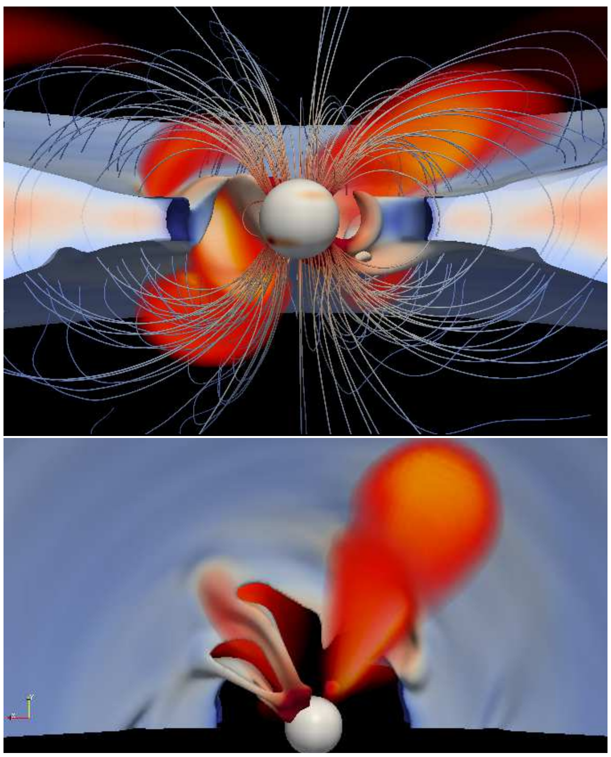

Figure 2: Effects of a storm of flares on the disk stability. Cutaway views of the star-disk system showing the mass density of the disk (blue) at $t = 26$ hours. The panels over-plot the three-dimensional volume rendering of the plasma temperature (in MK), showing the flaring loops (in red) linking the inner part of the disk with the star. The upper panel shows the star-disk system observed edge-on, whereas the lower panel shows the system observed pole-on. Selected magnetic field lines are overplotted in the upper panel.

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DISCUSSION

MATTEO GUAINAZZI: What kind of X-ray variability does your model predict? is it observed in the COUP sources?

SALVATORE ORLANDO: The X-ray variability depends on the rate of flares triggered. In the simulation with a single flare, we observe the fast rise and subsequent slow decay of X-ray emission characteristic of flares. In the simulation with a storm of flares, we observe a background emission due to the many small flares evolving simultaneousluy with superimposed local peaks due to the brightest flares. The X-ray variability found is consistent with that of YSOs observed by COUP.

DAVID BUCKLEY: Do you believe that your magnetospheric disk interaction models could be extrapolated to intermediate polar class of CVs, where accretion occurs from disrupted disc onto a magnetic white dwarf?

SALVATORE ORLANDO: Our model can be extrapolated (with appropriate scaling) to systems in which mass accretion occurs from a circumstellar disk, if relativistic effects can be neglected.